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OPTIMIZING AND SCALING OF HYPERVELOCITY LAUNCHERS AND COMPARISON WITH MEASURED DATA

A. J. Cable and J. R. DeWitt
ARO, Inc.

April 1967

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FOREWORD

The research reported herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 65402234.

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This technical report has been reviewed and is approved.

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Colonel, USAF
Director of Test

ABSTRACT

A recently developed theory for computing the internal ballistics of two-stage, light-gas launchers is described. This theory includes the effects of real gas, boundary layers, heat transfer, and piston friction. It has been applied to launchers ranging in size from 0.50- to 2.50-in. caliber and at velocities up to 32,000 ft/sec. Initial cycles for computation and experiment sometimes were obtained by "linear scaling" from various successful small launchers. The internal ballistics of several launchers, ranging in size from 0.5- to 2.5-in. caliber, have been measured and are in good agreement with the theoretical predictions. These measurements included piston velocity and projectile kinematics and, for the 2.5-in.-cal launcher, pressure measurements at a selected point. These data have given an indirect measure of such factors as piston friction and boundary-layer effects, allowing comparisons between guns of different sizes. It appears that the theory represents a distinct improvement over previous theories used by the authors and can now be used to predict performance of launcher configurations as yet untested. The simple linear scaling can be used to transfer successful launch cycles from one size of launcher to another of similar geometry but different scale. It can also assist in selecting launcher configurations to be tested by the more accurate theory or experiment.

CONTENTS

APPENDIXES

NOMENCLATURE

C	Dimensionless constant for spreading the shock wave
C_p	Local specific heat at constant pressure
$\overline{C}_p$	Total heat capacitance at constant pressure
C_v	Local specific heat at constant temperature
$\overline{C}_v$	Total heat capacitance at constant volume
D	Diameter
E	Specific energy
f	Dimensionless friction factor

L	Length
p	Static pressure
q	Dissipation pressure
R	Gas constant
t	Time
T_g	Temperature of gas
T_w	Temperature of launcher wall
U	Velocity
v	Specific volume
x	Distance
Z	Compressibility factor
γ	Dimensionless ratio of specific heats
ρ	Density
θ	$T_g/300$

SECTION I
INTRODUCTION

Hypervelocity launchers and aeroballistic ranges are now standard tools in the investigation of aerophysical phenomena. To develop launchers capable of higher velocities and the launching of more complex, fragile models, it is helpful to predict theoretically the internal ballistics of the launcher. Thus, launcher configurations and loading parameters may be varied to minimize the acceleration experienced by the model and maximize its muzzle velocity, in other words, to "optimize" launcher performance. The ability to measure the kinematics of the projectile using the microwave reflectometer developed by Hendrix (Ref. 1), coupled with the development of an improved method of computing the interior ballistics, has allowed the establishment of highly effective launch cycles for many different applications of the launchers of the von Kármán Gas Dynamics Facility (VKF).

SECTION II
COMPUTATION OF LAUNCHER PERFORMANCE

The method used for computing the launcher performance is based on the von Neumann-Richtmyer "q" method for finite difference calculation (Ref. 2). The gases in the powder chamber and pump tube, and the piston material, are divided into elements of mass, with half of the mass of each element concentrated at each side of the element in order to give a mass point system. The "q" method simulates the effects on shock waves arising from dissipative mechanisms such as viscosity and heat transfer, which tend to thicken the shocks, so that the mathematical surface of discontinuity is replaced by a thin layer, through which the gas properties vary continuously. The basis of the "q" method is the introduction of an artificial dissipation variable into the equations to give the shock waves a thickness comparable to one or more mass elements.

Thus, the equations of motion, energy, and continuity are written as

$$\rho_o (\partial U/\partial t) = -\partial (p + q)/\partial x$$

$$\partial E/\partial t + (p + q)\, \partial v/\partial t = 0$$

and

$$\rho_o (\partial v/\partial t) = \partial U/\partial x$$

An expression for q, meeting the requirements for the dissipation variable, is

$$q = [(C\Delta x)^2/v]\ (\partial U/\partial x)\ |\partial U/\partial x|$$

The above equations are converted into finite-difference form for the computer; and the gas properties, velocity, and displacement of each mass element are calculated at time increments compatible with the stability of the finite-difference equations. In the VKF calculations, the mass elements are usually divided as follows: five in the combustion chamber, three in the piston, and 30 in the pump tube. (These are varied at times to simulate different conditions in the launcher.)

The computer method assumes that combustion has been completed and that the combustion chamber is at constant pressure when the piston is released. Even with the relatively large combustion chambers of the VKF launchers, this is not true. Therefore, in the computer technique, a fictitious gas has been used. This gas has properties resembling those of the products of hydrogen-oxygen combustion in the presence of excess helium; i. e., a molecular weight of 6.36, a ratio of specific heats of 1.5, and a temperature of 2158°K. This gas was previously selected by the authors of an earlier computer program (Ref. 3), and it has been found that the projectile kinematics are reasonably well predicted when this gas is assumed in conjunction with the assumption of a chamber pressure which will produce a computed maximum piston velocity equal to the experimental piston velocity. Experimental piston velocities are obtained using wire probes, which are electrically shorted by the passage of the piston, and chronographs, which are gated by the probes. Using the fictitious value of driving pressure, the known piston and projectile weights and pump tube and projectile release pressures, the computation of launcher performance is carried out according to the flow scheme shown in Table I (Appendix II).

To the original program, the present authors have added corrections for the real gas effects of variation of specific heats and compressibility factors to match the National Bureau of Standards (NBS) (Ref. 4) hydrogen data. Also included are piston friction and plastic deformation of the piston as it enters the high pressure section of the launcher.

Approximation of gas friction at the wall boundaries is included and is based on the assumption of fully developed flow in the launch tube. The equation used is a form of the Darcy-Weisbach resistance equation as follows:

$$\Delta p = fL\rho U^2/(2D)$$

Approximation of heat transfer to the walls of the launcher is based on the Reynolds analogy and the above stated assumption of fully developed flow in the launch tube. The equation used is of the form

$$Q \approx f \rho \bar{C}_p U (T_g - T_w)$$

The friction factor, f, is read into the program as a constant. This is based on evidence that beyond a certain Reynolds number the friction factor is dependent only on the ratio of tube diameter to wall roughness. The latter ratio is not as large as one might think. Often passage of the projectile or its sabot leaves the launch tube bore quite rough until it is cleaned after the firing.

For the maximum Reynolds numbers (of the order of 10^8) developed in the higher velocity launch cycles, the friction factor will be constant for any but a "smooth" bore, which is generally not obtained in actual hardware. This means that for the early part of the cycle and for low velocity areas such as the breech end of the launch tube, the constant friction factor used is smaller than would seem to be appropriate. However, these are the regions where fully developed flow is least likely to be realized. This will tend to decrease the error introduced by the assumption of a constant friction factor. Thus, a reasonable approximation of the friction factor may be obtained from hardware dimensions only.

Plastic deformation of the piston is included to account for the piston energy losses produced by extrusion of the piston into the change of area in the high pressure section. The deformation pressure includes effects of high strain rate in the plastic. The value of 40,000 psi selected gives accurate predictions of launcher performance for the various launcher configurations in use.

Real gas effects are included in the computer program. The form of the gas law employed is

$$pv = ZRT_g$$

The compressibility factor Z is that employed by the National Bureau of Standards for hydrogen, viz.,

$$Z = \exp\left(\frac{a + b\theta}{v} + \frac{c}{\theta v^2}\right)$$

where $\theta = T_g/300$ and a, b, and c are constants.

The relationship of temperature to internal energy is

$$T_g = E/\bar{C}_v$$

so that the gas law becomes

$$pv = ZRE/\bar{C}_v$$

where $\bar{C}_V$ is an overall heat capacitance at constant volume.

For the variation of specific heats with changing conditions, the National Bureau of Standards data for hydrogen are approximated by a polynomial curve fit for temperature dependence at one atmosphere pressure plus a pressure dependence term for correction for varying pressure. The form of the resulting equation for C_p and C_V is

$$C_p \text{ or } C_v = a T_g^3 + b T_g^2 + c T_g + d + p \left(\frac{1}{e T_g + g} + h\right)$$

where a, b, c, d, e, g, and h are constants determined separately for C_p and C_V. The determination of the overall heat capacitance can thus be performed by considering a two-path process (or integration) so that

$$\bar{C}_p \text{ or } \bar{C}_v = \frac{\int_{T_o}^{T_g} (a T_g^3 + b T_g^2 + C T_g + d)\, dT}{T_g - T_o} + \frac{\int_{p_o}^{p} p\left(\frac{1}{e T_g + g} + h\right) dp}{p - p_o}$$

where T_o and p_o are the initial conditions for the calculation (generally 300°K and 1 atm in present usage). By this technique, the specific heats are fitted to the National Bureau of Standards data within 2 percent over the normal range of operating conditions for the light gas launchers at the AEDC.

Typical values used for the various factors are: coefficient of friction on the piston, 0.005; plastic deformation of the piston, 40,000 psi; and friction factor of gas in the launch tube, 0.0056 for a 2.5-in. diameter, 0.0070 for a 1.0-in. diameter, and 0.0086 for a 0.5-in. diameter. The same roughness criterion was used for each launch tube, and thus the value of this factor varies with launch tube diameter. It has been found in numerous calculations that the above values of these factors give good results for a wide range of launcher configurations and shot conditions.

SECTION III
COMPARISON OF THEORETICAL PREDICTIONS AND EXPERIMENTAL RESULTS

Previous comparisons of the measured accelerations and those predicted by the computer program of the Naval Ordnance Laboratory (NOL) (Ref. 3) were given in Ref. 5, where reasonable agreement was obtained except for the higher velocity part of the motion. It was subsequently found in attempts to predict the motion for projectile velocities near 30,000 fps that the NOL theory overpredicted the launch velocity by the order of 40 percent, although it still gave reasonable prediction of peak accelerations.

In this section, similar comparisons of predicted and computed launcher kinematics will be made to indicate the accuracy with which launch cycles may be predicted with the improved launcher performance theory mentioned in the previous section. These examples will be divided into three parts consisting of: (1) the VKF Impact Range 0.5-in.-cal launchers, (2) the K Range 1.0-in.-cal launcher, and (3) the G Range 2.5-in.-cal launcher.

3.1 IMPACT RANGE S201 AND S102 LAUNCHERS

The impact ranges in the VKF have for some time been using the S201, 0.5-in.-cal launcher which has a 2.0-in. bore, 131.0-in.-long pump tube, and an abrupt change of section at the launch tube-pump tube joint. Dimensions of the launcher are given in Table II. This launcher normally uses a 180-gm piston and 450- to 500-psia pump tube initial pressure and was, for some time, launching models of 1.4-gm in-gun weight at maximum velocities of the order of 27,000 fps. This velocity was later raised to 30,100 fps with 1.0-gm projectiles and to 31,900 fps with 0.7-gm projectiles, by use of a new launch cycle found by the application of the principle of linear scaling, which will be discussed later. These projectiles were made of Lexan® (polycarbonate resin) and were restrained against premature movement down the launch tube by a 0.010-in. interference fit on the diameter. Previous tests had indicated that this interference corresponds to a release pressure of 1200 to 2400 psi.

Table III lists the comparisons made, giving full details of the shot conditions used. Figure 1 (Appendix I) shows a comparison of the measured and computed base pressure histories for 0.96- and 0.97-gm polycarbonate slugs launched at 30,100 and 29,700 fps, respectively.

The "constant base pressure" referred to in Fig. 1 and elsewhere in this report is the computed constant pressure that would produce equal muzzle velocity; thus, it is also the minimum pressure with which that muzzle velocity may be attained for the given mass launched and launch tube dimensions.

As stated above, these models are believed to have had a release pressure of from 1200 to 2400 psi. The release pressure used in the computation was 1800 psi, and base pressures of shot T994 closely follow those computed, except for the magnitude of the peak which is difficult to measure accurately because of resolution limitations of the microwave reflectometer system. The other shot, T993, indicates a lower but slightly broader base pressure peak and was launched about 400 fps faster than was shot 994. Of course, by slightly changing the values of the piston and boundary-layer friction parameters in the computation, a closer approximation to the measured internal ballistics can be obtained. The predicted launch velocity is from 80 fps high to 320 fps low (+0. 3 to -1. 3 percent). The maximum pressure computed was 565, 000 psia. The value of this pressure is critically controlled by the assumed shape of the transition between the pump tube and launch tube. In this launcher, there is an abrupt transition, which gives rise to this very high computed peak pressure for a short period of time.

As part of the development of the impact range launchers to produce consistent velocities of 30, 000 fps and above, the S102 configuration was tested. This also has a 0. 5-in. -cal launch tube, but is has a much larger pump tube of 2. 5-in. bore and 297-in. length. The launch tube-pump tube joint has a taper of one in eight (7°7'). Using a launch cycle developed by the computations, a 1. 264-gm in-gun weight, consisting of a 0. 125-in. -diam aluminum sphere and its sabot, was launched at 30, 300 fps. Projectile retention was accomplished at the launch tube-high pressure section joint by a hemispherical, grooved diaphragm. These diaphragms were designed and tested to give a release pressure of approximately 18, 000 psi. Hemispherical diaphragms were developed and used, because petals were lost from the original flat diaphragm design when used for these firing conditions. Figure 2 shows a comparison of predicted and measured base pressure histories for the 30, 300-fps shot, and the agreement is reasonable. The launch velocity predicted is 4. 7 percent high.

3.2 K03, 1.0-IN.-CAL LAUNCHER

The K03, 1. 0-in. -cal launcher has a 165. 6-in. -long launch tube and a 2. 3-in. bore, 175. 2-in. -long pump tube with an abrupt (hemispherical) change of area at the pump tube-launch tube transition. Figure 3 shows a comparison of the computed and measured base pressure histories for two, 4. 7-gm, polycarbonate slugs launched at 16, 340 and 16, 980 fps, respectively, and quite reasonable agreement is obtained. Shots similar to these were fired as part of a study described in Ref. 6, wherein it was noted that the NOL computer program then used predicted a considerable peak in acceleration near the muzzle for these conditions. With the VKF program described in an earlier section, this still occurs but to a much lesser extent, and there is some indication from the measured acceleration that a "weak" peak does occur. Subsequent to the tests described in Ref. 6, it was also proved that this particular set of shot conditions was very sensitive to pump tube pressure (around 400 psia). A 2.5-percent variation in pump tube pressure gave a similar variation in velocity, whereas at 475-psia pump tube pressure, the velocity would only vary by 0.6 percent for 2.5-percent change in pump tube charge pressure. The launch velocity is overpredicted by 0.1 percent in one case and under by 3.7 percent in the other.

3.3 G03, 2.5-IN.-CAL LAUNCHER

The G03 launcher has a 2.5-in.-cal, 500-in.-long launch tube and an 8.0-in.-bore, 607-in.-long pump tube with an abrupt change in area at the transition between the pump tube and launch tube bores. Its high pressure section is rated at 170,000 psi, and the initial pump tube charge is limited by safety considerations to 215 psia of hydrogen. Figure 4 shows the comparison of measured and computed base pressure histories for a 176-gm projectile (1.0-in. base diameter, 15-deg semi-angle cone) launched at 22,700 fps, and the agreement is good, as is the prediction of launch velocity which is 2.7 percent high. The initial pressure ahead of the projectile in this shot was 10 mm Hg, and this pressure, considered with the low frequency (4 kHz) of the microwave reflectometer (dependent on launcher caliber) produced distortion of the microwave signal by plasma absorption or reflection at projectile velocities above 15,000 fps. This velocity was reached after the projectile had traversed 30 percent of the launch tube, which is where these data are terminated in the figure. Figure 5 is a black and white reproduction of a color-schlieren photograph taken of a similar cone launched at 23,460 fps.

Figure 6 shows comparisons for lighter in-gun weight combinations of cones and sabots launched at about 21,500 fps. The agreement between the measured and computed base pressures is quite reasonable, and the computed launch velocities vary from 0.5 percent high to 0.8 percent low.

The ability of the VKF performance theory to predict pressures in the gun is illustrated by Fig. 7 and Table IV. Figure 7 shows a comparison of the pressures measured at a point in the launch tube 35.6 in. toward the muzzle from the model loading portion. It was not considered desirable to weaken the high pressure section to measure pressures nearer to the region of peak pressures. Because of difficulty in identifying the start of the pressure rise from the measurements, the time of the measured maximum pressures has been placed at the same time as the computed maximum. The computed pressure starts to rise when the projectile moves past the position of the pressure transducer. The agreement shown is quite good. Table IV lists the measured and computed maxima, where it can be seen that the average measured maxima are slightly less than those computed. Out of the seven shots considered, two give rather poor agreement, one being 25.7 percent lower and the other 13.1 percent higher than the computed value. The better agreement of the pressures of the other five shots, coupled with the fact that the base pressure histories of these two shots show no unusual features, leads one to the belief that these errors are mainly caused by the measurements. If these are neglected, the computed maximum pressure is 3.0 percent greater than the mean of the measured values. This agreement, both in magnitude and in rise and decay times, gives us confidence in the validity of the peak pressures predicted by the computer program.

SECTION IV
LINEAR SCALING OF HYPERVELOCITY LAUNCHERS

Early in 1963, a series of shots was made using the Mark III, 0.375-in.-cal launcher (dimensions given in Table II), which launched 0.48-gm Lexan slugs at velocities ranging from 27,000 to 32,000 fps with nominally identical charge conditions. These were: 0.48-gm projectile, 85-gm piston at peak speed of 4700 fps, and 160-psia hydrogen pump tube pressure. The projectile was retained by being made 0.010 in. oversize in diameter, and some of the variations of launch velocity were caused by variations in release pressure of the projectile. The charging conditions for these shots were determined on the basis of the method of Stephenson (Ref. 7), which assumes that the projectile is propelled by an isentropically expanding gas from an infinite reservoir at some initial pressure, corresponding to the peak pressure produced by the actual piston motion. Empirical corrections for the effects of final temperature (peak), piston reversal, and initial projectile motion were applied, and this theory gave a reasonable prediction of launch velocity, but probably did not correctly predict peak pressures in the launcher or the base pressures experienced by the model. Considerable damage occurred in the high pressure section and at its joint with the launch tube during these firings, and it was necessary to hone these components between shots. This shot condition has been analyzed recently by the new computation method, and the computed base pressure history of this shot is shown as Fig. 8, as are the calculated launch velocity and peak pressure. It can be seen that the calculated maximum base pressure of 83,000 psi and peak pressure of 405,000 psi, if true, would explain the damage experienced in the tests.

If it is assumed that piston velocity and pump tube pressure remain constant and the possibly nonlinear scaling of various losses is ignored, it is possible to scale launcher dimensions linearly and obtain the same launch velocity from guns of different sizes. The launch mass scales as the third power of the scale factor, and since the force propelling the projectile will vary as the square of the scaling factor, the accelerations will vary inversely with the scale factor. Of course, it is the base pressure on the projectile which affects model stresses, and this is unchanged. So, if the model is scaled too, the model failing acceleration also varies inversely with scale. The piston weight is scaled such that the piston weight per unit pump tube volume remains constant.

The S201, 0.5-in.-cal launcher is almost a scaled-up version of an earlier VKF launcher, namely the 0.375-in. Mark III gun already mentioned (dimensions given in Table II). Actually, the S201 gun has a (relatively) slightly shorter and wider pump tube. For some time after the S201 launcher had been brought into service, the following charging conditions were used: 180-gm piston and 450- to 500-psia hydrogen pump tube pressure. Recently, the similarity of the former Mark III gun and the present S201 gun and the possibility of linear scaling were pointed out by J. Lukasiewicz (Ref. 8). New S201 charge conditions were scaled from the highest velocity shot with the Mark III launcher. For the S201, these give a piston weight of 130 gm and a pump tube charge of 160-psia hydrogen. The scaled projectile mass is 1.096 gm. A series of shots was fired using the S201 launcher with projectiles weighing 0.96 gm and with peak piston velocities of 5100 to 5400 fps, producing launch velocities ranging from 29,500 to 30,100 fps, which are similar to those obtained previously with the Mark III launcher. The piston velocities were a little higher than the 4700 fps of the Mark III firings. A comparison of the computed and measured base pressure histories for two of these firings is shown as Fig. 1 and was discussed in the previous section. Although the scaling was not perfect, results were such as to support the use of linear scaling for similar problems.

SECTION V
APPLICATION OF SCALING TO A 2.5-IN.-CAL LAUNCHER

It is of interest to consider scaling the Mark III launcher up to the 2.5-in. caliber of the Range G launcher. In this case, the launch tube would be 66.6 ft long (60 percent longer than that of the present G03 launcher). The pump tube dimensions would be 10.5-in. bore and 70-ft length (approximately one-third greater in length and diameter than the G03). The projectile weight scales to 142 gm, and the piston weight to

26.1 kg. Figure 9 shows the predicted pressure history for such shot conditions. The launch velocity and peak pressure in the high pressure section for this shot are nearly identical to those of the actual Mark III (0.375-in.-cal) shot (Fig. 8), and the maximum base pressure of 78,000 psia is near to that of the Mark III (83,000 psia) though somewhat less than that of the S201 (115,000 psia). It is further indicated by comparing the computed base pressures for these three launchers in Fig. 10 that simple linear scaling is possible over quite a wide range of launcher sizes. The particular launch condition for the scaled G03 launcher will prove difficult to reach in practice, because of the difficulty of the design of a large high pressure section to withstand the calculated 400,000 psi, and probably only a simple polycarbonate slug would withstand the calculated base pressure loading of 78,000 psia.

SECTION VI
CONCLUSIONS

It has been shown for a number of launchers ranging in caliber from 0.50 to 2.5 in. that the improved launcher performance theory in use at the VKF is capable of predicting high speed launcher performance accurately. The values of the parameters controlling piston friction, boundary-layer friction, and piston plastic flow effects which have been developed are shown to be applicable to a wide variation of launcher parameters. Thus, the computational method enables the performance of launchers as yet untested to be predicted with increased confidence, and should allow the design of better launcher configurations.

The use of the simple linear scaling approach allows the transfer of successful launch cycles from one size of launcher to another. It also assists in selecting launcher configurations to be examined exhaustively by the more accurate, but more complicated, computer calculation.

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APPENDIXES

I. ILLUSTRATIONS

II. TABLES

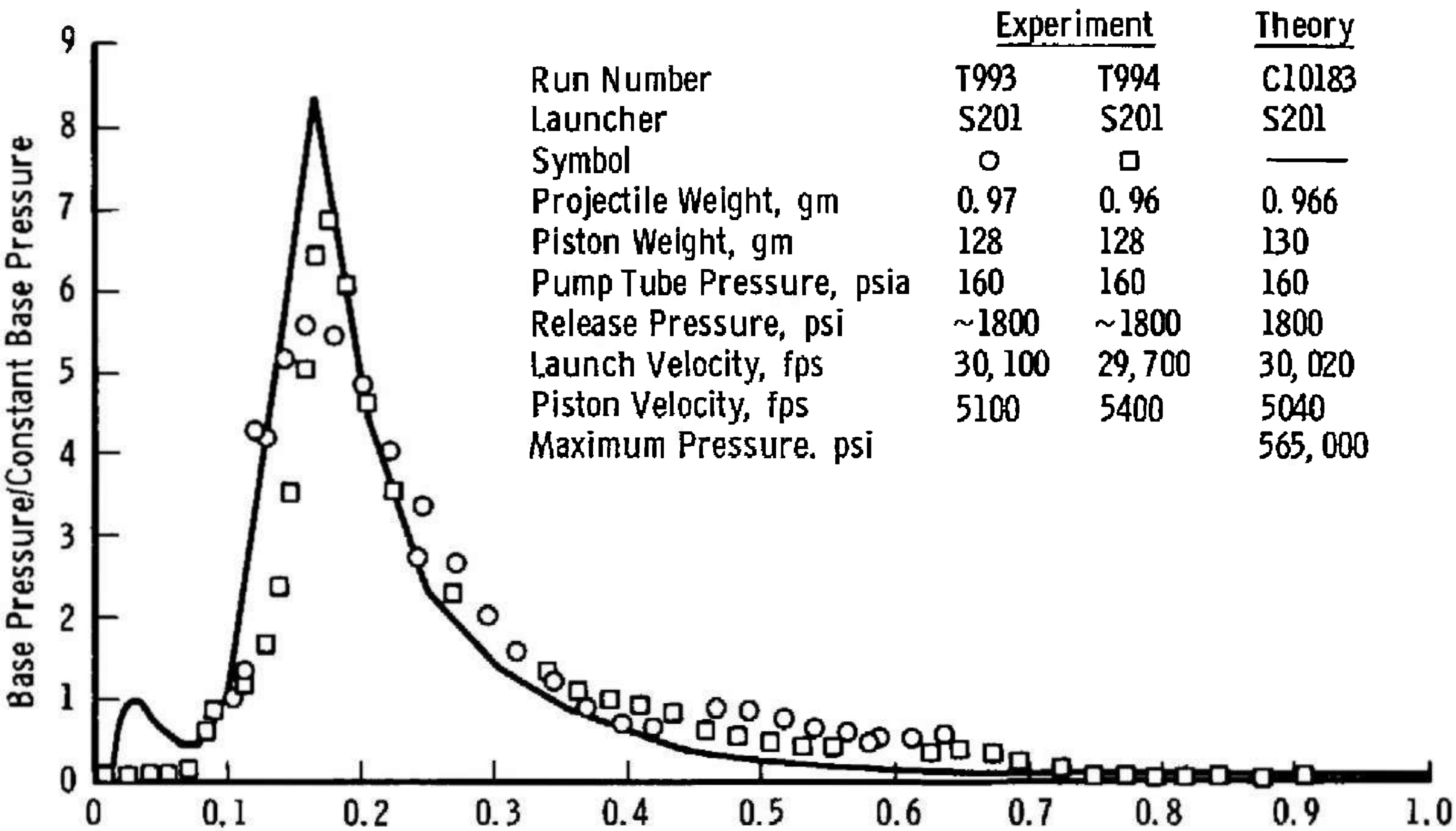

Fig. 1 Comparison of Measured and Computed Base Pressure Histories for 0.97-gm Projectiles Launched at 30,000 ft/sec by S201, 0.5-in.-cal Launcher

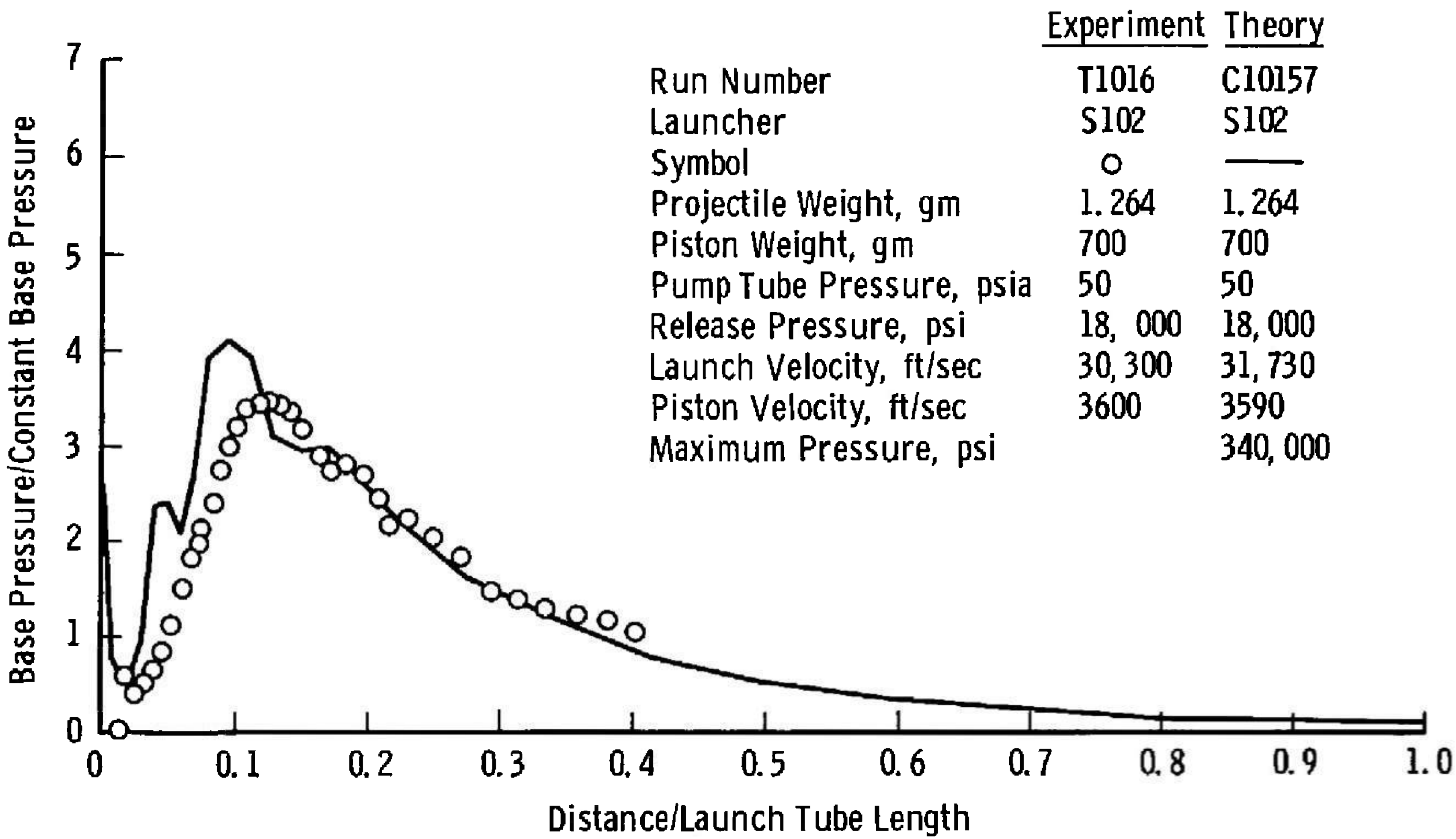

Fig. 2 Comparison of Measured and Computed Base Pressure Histories for 1.264-gm Projectile Launched at 30,300 ft/sec by S102, 0.5-in.-cal Launcher

	Experiment		Theory
Run Number	K1237	K1238	C11072
Launcher	K03-1"	K03-1"	K03-1"
Symbol	○	□	———
Projectile Weight, gm	4.786	4.704	4.786
Piston Weight, gm	765	765	765
Pump Tube Pressure, psia	400.9	402.9	400
Release Pressure, psi	5000	5000	5000
Launch Velocity, ft/sec	16,340	16,980	15,360
Piston Velocity, ft/sec	2700	2720	2727
Maximum Pressure, psi			166,000

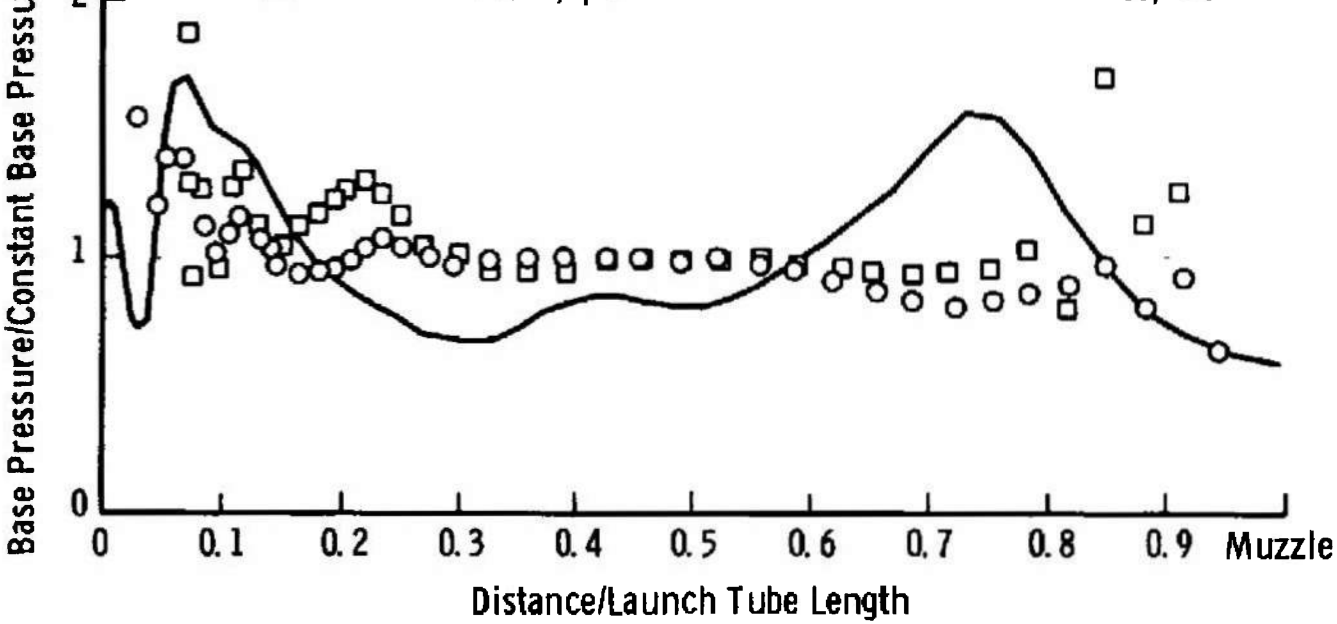

Fig. 3 Comparison of Measured and Computed Base Pressure Histories for 4.8-gm Projectiles at 16,340 to 16,980 ft/sec by K03, 1-in.-cal Launcher

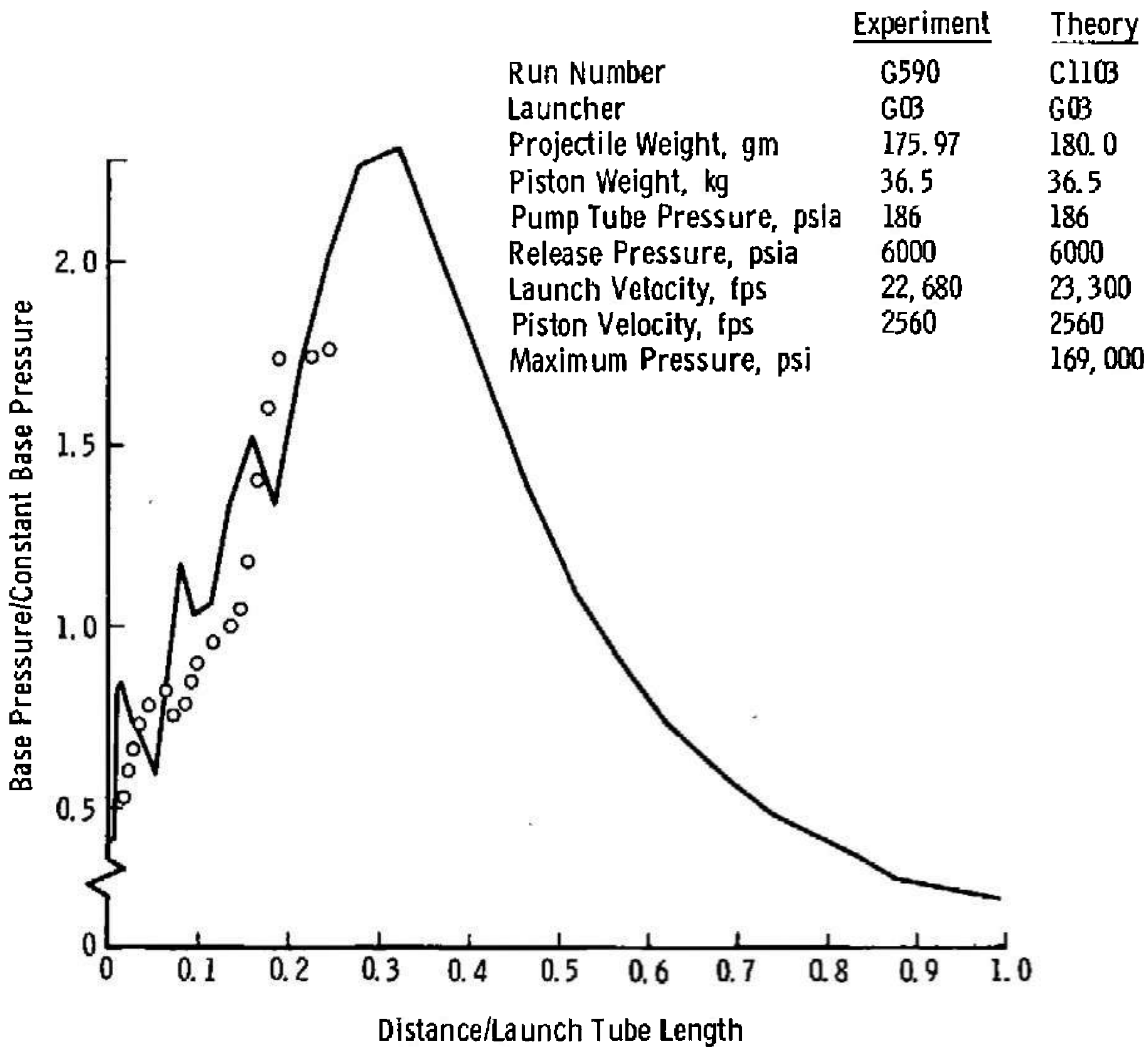

Fig. 4 Comparison of Measured and Computed Acceleration Histories of 176-gm, 1.0-in.-diam Cone Launched at 22,720 ft/sec by G03, 2.5-in.-cal Launcher

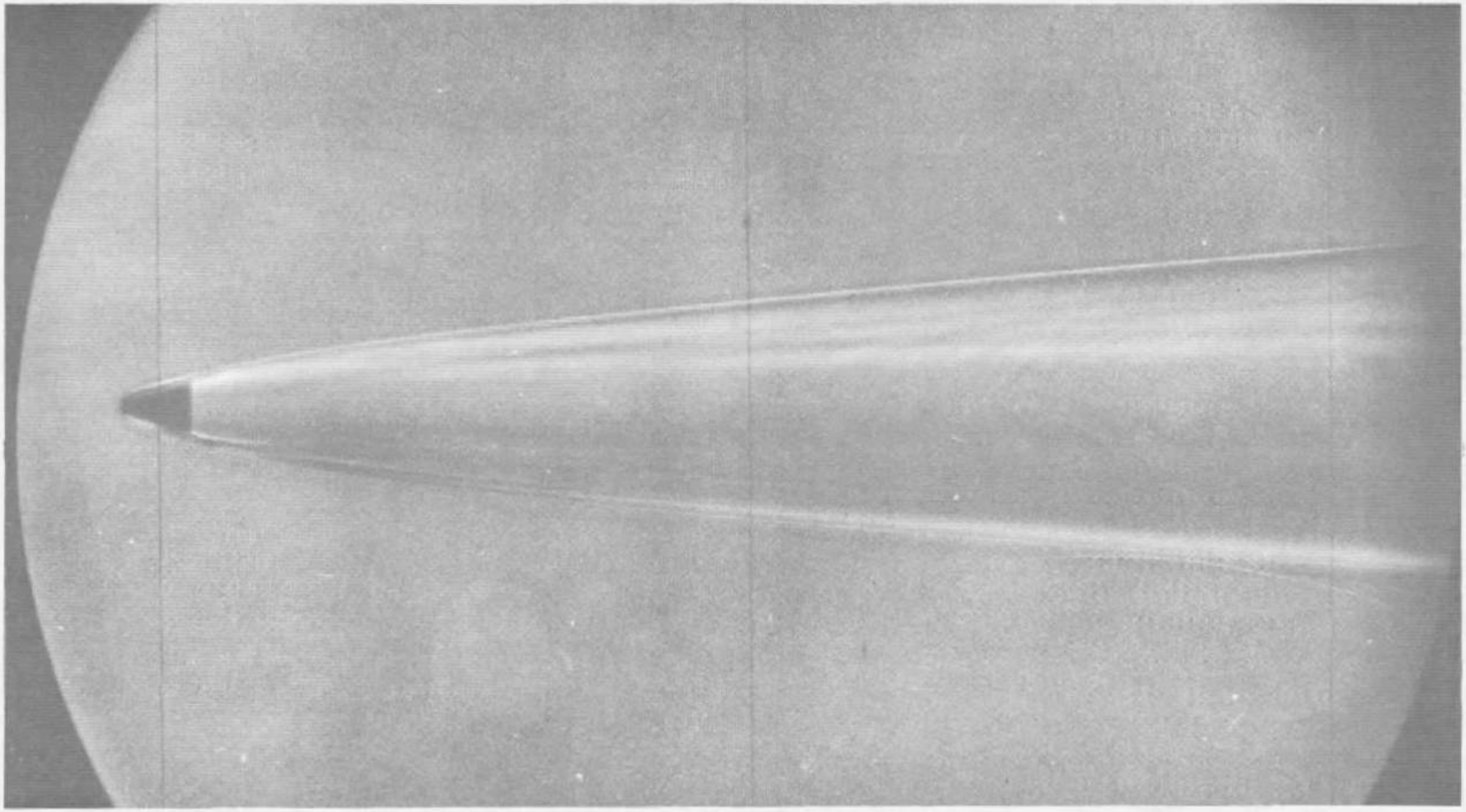

Fig. 5 15-deg, Semi-Angle, 1.0-in. Base Diameter Cone Launched at 23,460 ft/sec into 30-mm-Hg Range Pressure (Black and White Reproduction of Color Schlieren)

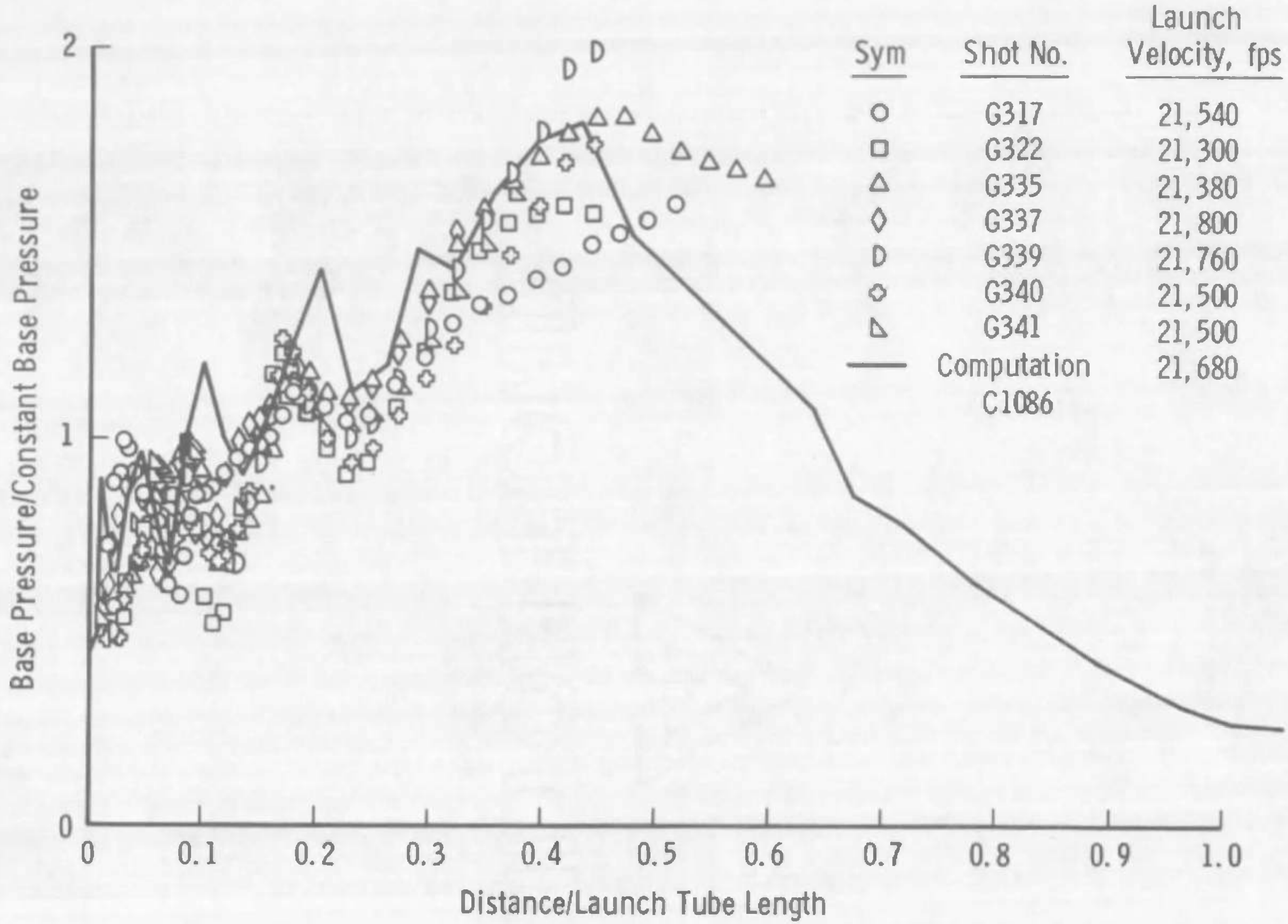

Fig. 6 Comparison of Measured and Computed Base Pressure Histories for 6-deg, Semi-Angle Cones Launched at 21,500 ft/sec by G03, 2.5-in.-cal Launcher

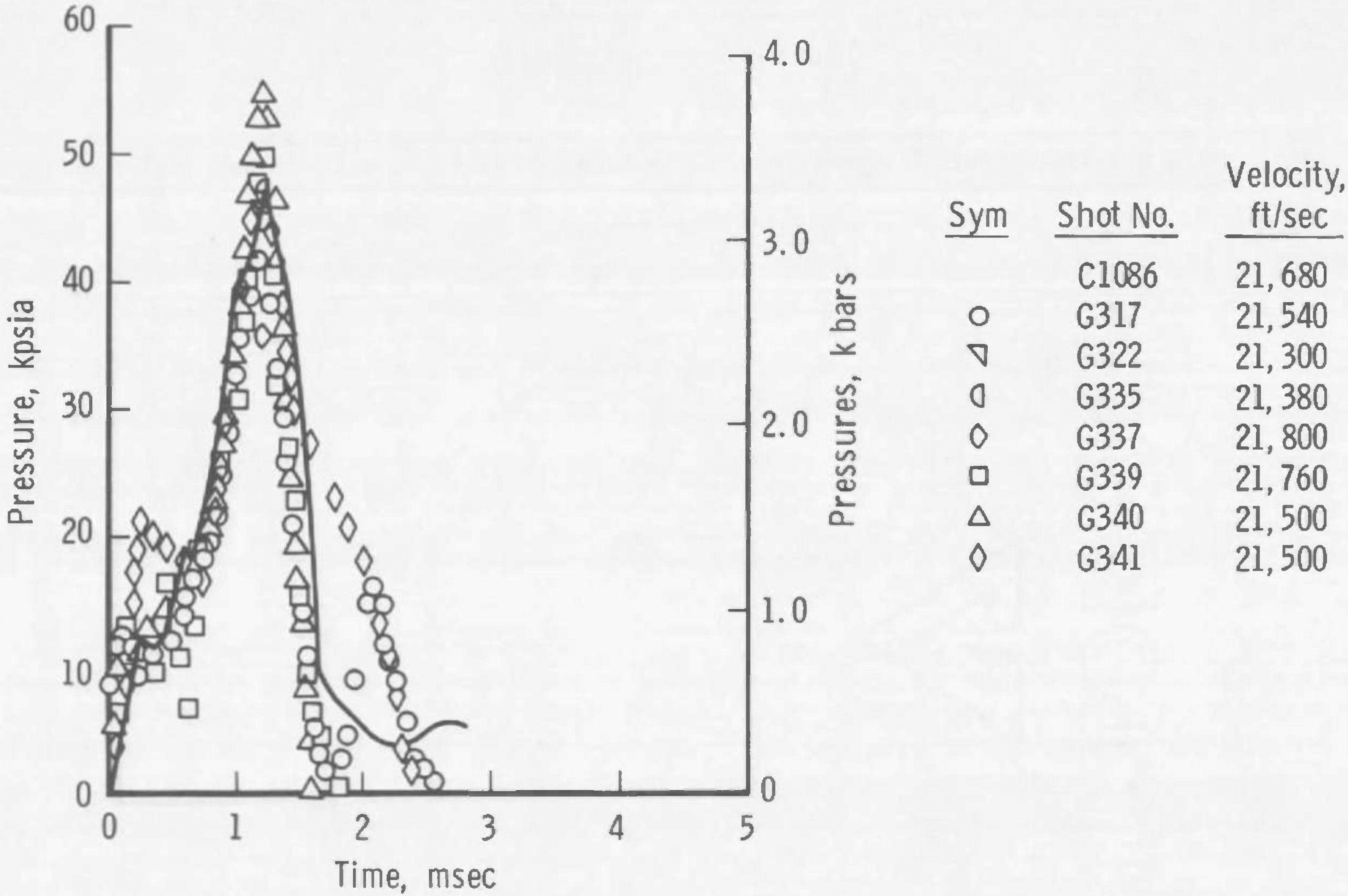

Fig. 7 Comparison of Measured and Computed Maximum Pressures in Launch Tube 35.6 in. from Model Loading Position for G03 Launcher

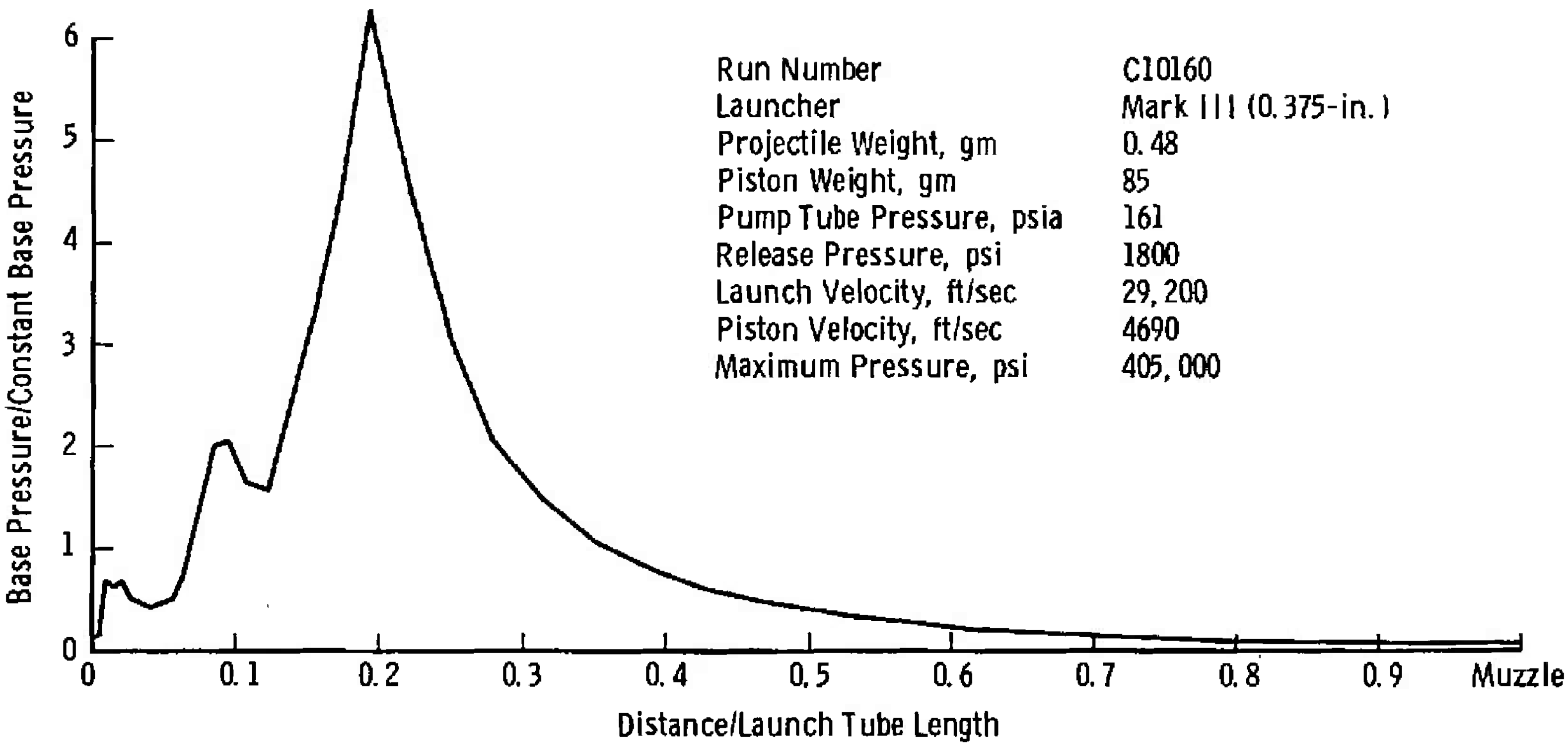

Fig. 8 Predicted Base Pressure History for 0.48-gm Projectiles Launched at 27,000 to 32,000 ft/sec by the Mark III, 0.375-in.-cal Launcher

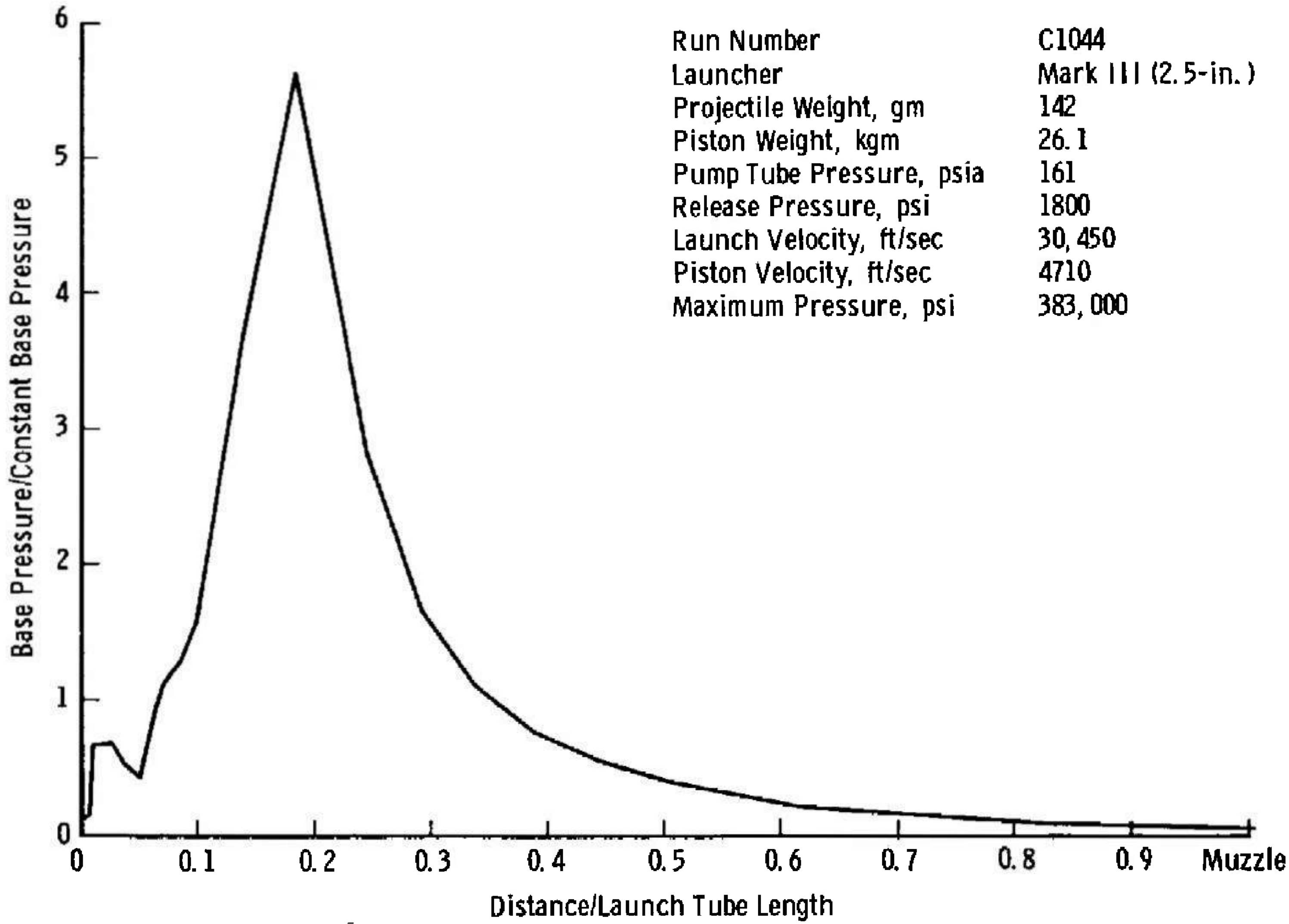

Fig. 9 Predicted Base Pressure History for 142-gm Projectile Launched by Mark III Launcher Scaled to 2.5-in. Caliber

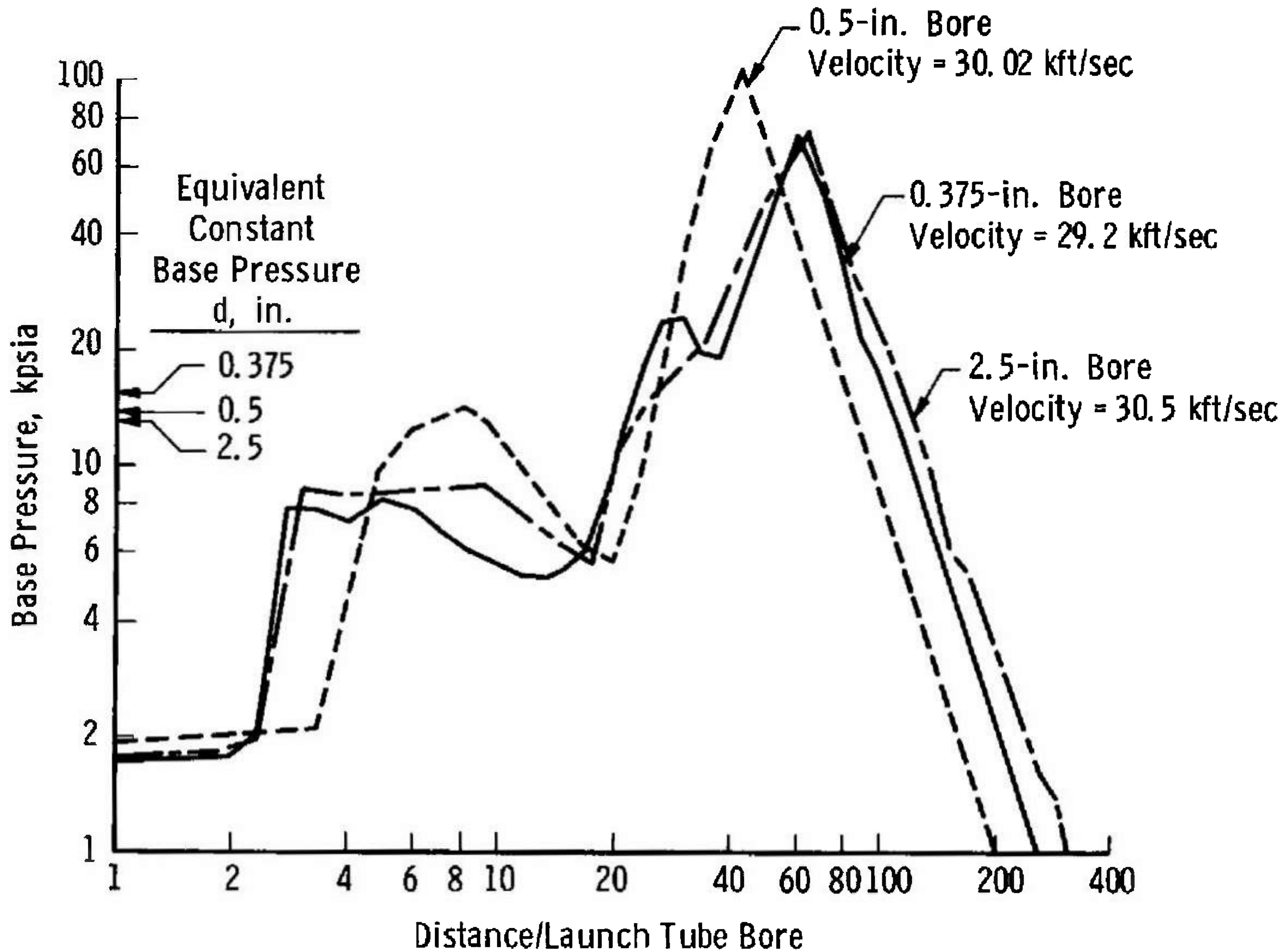

Fig. 10 Computer Base Pressures for Linearly Scaled Guns

TABLE I
FLOW SCHEME FOR COMPUTATIONS

Zero variables

Read and print input parameters

Compute displacement and volume of mass elements

Compute pressure, temperature, gas constants, etc., of elements

Compute total energy of system

Print initial conditions

Increment time

Compute drag on elements

Compute acceleration, velocity, and displacement of elements

Compute new volumes of elements

Compute volumes and energy in barrel for heat transfer

Compute gas constants, pressure, temperature, etc., of elements

Compute heat transfer

Check for projectile exit from launch tube;
printout, go to new problem, or end

Determine time increment

Rotate indices and sum energy

Check for printout time

TABLE II
LAUNCHER DIMENSIONS

Launcher	Launch Tube Diameter (d_ℓ), in.	Launch Tube Length (ℓ_ℓ), in.	Pump Tube Diameter (d_p), in.	Pump Tube Length (ℓ_p), in.	d_p/d_ℓ	ℓ_ℓ/d_ℓ	ℓ_p/d_ℓ	ℓ_p/d_p
Mark III	0.375	115.00	1.58	126.00	4.21	306.67	336.00	79.75
S201	0.500	130.66	2.00	131.00	4.00	261.32	262.00	65.50
S102	0.500	125.34	2.50	297.08	5.00	250.68	594.16	118.83
K03-1	1.000	165.60	2.30	175.20	2.30	165.60	175.20	76.17
G03	2.500	499.84	8.00	607.06	3.20	199.94	242.82	75.88
Scaled G	2.500	839.20	10.50	840.00	4.21	306.67	336.00	79.75

1 in. = 2.54 cm

TABLE III
SHOT COMPARISONS

Shot No.‡	Launcher	Projectile Weight, gm	Projectile Velocity, ft/sec	Piston Weight, gm	Piston Velocity, ft/sec	Pump Tube Pressure, psia	Release Pressure, psia	Peak Pressure (Calculated), psia
T993	S201	0.966	30,100	128	5100*	160.0	1,200-2,400	----
T994	S201	0.962	29,700	128	5400*	160.0	1,200-2,400	----
C10183	S201	0.966	30,020	130	5043	160.0	1,800	565,000
T1016	S102	1.264	30,300	700	3600	50.0	18,000	----
C10157	S102	1.264	31,730	700	3590	50.0	18,000	340,400
K1237	K03-1	4.786	16,340	765	2700	400.9	5,000	----
K1238	K03-1	4.704	16,980	765	2720	402.9	5,000	----
C11072	K03-1	4.786	16,364	765	2727	400.0	5,000	166,000
C590	G03	175.97	22,680	36,500	2560	186.0	6,000	----
C1103	G03	180.00	23,300	36,500	2560	186.0	6,000	169,000
G317	G03	157.24	21,540	38,300	2390	201.0	5,500	----
G322	G03	155.31	21,300	37,900	2380	201.0	5,500	----
G335	G03	149.21	21,380	37,900	2300	201.0	5,500	----
G337	G03	158.18	21,800	38,600	----	202.0	5,500	----
G339	G03	153.59	21,760	37,600	----	200.0	5,500	----
G340	G03	158.47	21,500	38,400	----	197.0	5,500	----
G341	G03	153.19	21,500	37,300	----	198.0	5,500	----
C1086	G03	157.24	21,680	38,300	2390	201.0	5,500	137,000
K53	Mark III	0.48	30,500	85	4700	160.0	Thought to be 1,800	----
K54	Mark III	0.48	32,000	85	4700	160.0		----
K55	Mark III	0.48	27,000	85	4700	160.0		----
K56	Mark III	0.49	27,000	85	4700	160.0		----
C10160	Mark III	0.48	29,200	85	4690	161.0	1,800	405,000
C1044	Scaled G	142.00	30,450	26,100	4710	160.0	1,800	383,000

*Extrapolated from powder charge-piston velocity data obtained up to 5,000 ft/sec.

‡The prefix C denotes a theoretical result; other shots represent experimental data.

TABLE IV
COMPARISON OF MEASURED AND COMPUTED MAXIMUM PRESSURES IN THE LAUNCH TUBE 35.6 IN. FROM THE MODEL LOADING POSITION FOR G03 LAUNCHER

	Launch Velocity, ft/sec	Pressure, psia	Difference from Computed, percent
Computation 1086	21, 680	48, 300	——
Shot 317	21, 540	44, 900	- 7.0
322	21, 300	45, 200	- 6.4
335	21, 375	47, 300	- 2.1
337	21, 800	35, 900	-25.7
339	21, 760	49, 800	+ 3.1
340	21, 500	54, 900	+13.7
341	21, 500	47, 100	- 2.5
Mean all shots		46, 400	- 3.9
Mean except 337 and 340		46, 900	- 3.0

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13 ABSTRACT

A recently developed theory for computing the internal ballistics of two-stage, light-gas launchers is described. This theory includes the effects of real gas, boundary layers, heat transfer, and piston friction. It has been applied to launchers ranging in size from 0.50- to 2.50-in. caliber and at velocities up to 32,000 ft/sec. Initial cycles for computation and experiment sometimes were obtained by "linear scaling" from various successful small launchers. The internal ballistics of several launchers, ranging in size from 0.5- to 2.5-in. caliber, have been measured and are in good agreement with the theoretical predictions. These measurements included piston velocity and projectile kinematics and, for the 2.5-in.-cal launcher, pressure measurements at a selected point. These data have given an indirect measure of such factors as piston friction and boundary-layer effects, allowing comparisons between guns of different sizes. It appears that the theory represents a distinct improvement over previous theories used by the authors and can now be used to predict performance of launcher configurations as yet untested. The simple linear scaling can be used to transfer successful launch cycles from one size of launcher to another of similar geometry but different scale. It can also assist in selecting launcher configurations to be tested by the more accurate theory or experiment.

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